THE ORIGIN OF A CHEMICALLY ENRICHED Lyα ABSORPTION SYSTEM AT $z = 0.167$[1]

HSIAO-WEN CHEN and JASON X. PROCHASKA

Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101, U.S.A.

hchen,xavier@ociw.edu

[1]Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5–26555.

Received ______________; accepted ______________

Accepted by The Astrophysical Journal Letters

ABSTRACT

We present the first detailed analysis of the chemical abundances, ionization state, and origin of a partial Lyman limit system ($N(\mathrm{H~I}) \approx 10^{16}$ cm^{-2}) at low redshift ($z = 0.167$ towards PKS0405−1219). Two galaxies at $\approx 70~h^{-1}$ kpc projected distance to the QSO have been identified at the absorber redshift. We analyze an echelle spectrum of the QSO obtained with the Space Telescope Imaging Spectrograph and find that this absorption system exhibits associated lines produced by C^+, N^+, O^0, Si^+, Si^{++}, Si^{+3}, Fe^+, and Fe^{++}, and most interestingly, O^{+5} and N^{+4}. The results of our analysis show that the partial Lyman limit system traced by various ions is likely to be embedded in a collisionally ionized O VI gas of larger spatial extent. Furthermore, the partial Lyman limit system appears to have a metallicity of *at least* 1/10 solar and most likely solar or super solar despite the fact that no luminous galaxies are seen within a projected distance $\rho = 60~h^{-1}$ kpc to the QSO. Finally, adopting the temperature estimated for the hot gas $T \approx 2.5 \times 10^5$ K and assuming a simple isothermal halo, we estimate that the galaxy or galaxy group that supports the extended gas may have a total mass $\approx 1.5 \times 10^{12} M_\odot$ and a gas number density $\lesssim 3 \times 10^{-5}$ cm^{-3}.

Subject headings: galaxies: evolution—quasars: absorption lines

1. INTRODUCTION

The absorption line systems observed in the spectra of background QSOs have proven to be a sensitive probe to the physical conditions of intervening gas. In particular, kinematic studies and chemical abundance measurements of Lyα absorption systems of neutral hydrogen column density $N(\text{H I}) > 10^{16}$ cm^{-2} at $z > 1.7$ provide a direct assessment of the dynamical characteristics and chemical enrichment history of the absorbers (Prochaska & Wolfe 1997, 1998, 1999, 2000; Pettini et al. 1997; Rauch, Haehnelt, & Steinmetz 1997; Haehnelt, Steinmetz, & Rauch 1998; Prochaska 1999). While these absorption systems are generally believed to originate in or near galaxies (because of high H I column density and/or large metal content), it has been extremely difficult to directly associate the properties of absorption line systems with the properties of galaxies because distant galaxies are faint. On the other hand, at redshift $z \lesssim 1$, where galaxies are routinely identified, various galaxy surveys targeted at QSO fields have shown that luminous galaxies possess extended Mg II gas out to $\approx 40\ h^{-1}$ kpc[†] (e.g. Bergeron & Boissé 1991), extended C IV gas out to 100 h^{-1} kpc (Chen et al. 2000a), and extended neutral hydrogen gas out to $\approx 180\ h^{-1}$ kpc (Lanzetta et al. 1995; Chen et al. 1998, 2000b). But the origin and physical environment of the extended gas is largely unknown, because of limited information regarding kinematics and metallicity of the gas. The primary difficulty arises in acquiring a high-quality QSO spectrum of wide UV spectral coverage.

To address this issue, we are initiating a survey of Lyα absorption systems for which high resolution, high signal-to-noise ratio (SNR) UV spectra are available and for which the absorbing galaxies have been identified. In this *Letter*, we present the first results of this survey based on the study of a Lyα absorption system at $z = 0.167$ toward PKS0405−1219 ($z_{em} = 0.5726$), for which high-quality echelle spectra have been obtained with the Hubble Space Telescope (HST) using the Space Telescope Imaging Spectrograph (STIS). This system is especially interesting for two reasons.

[†]We adopt a standard Friedmann cosmology of dimensionless Hubble constant $h = H_0/(100$ km s^{-1} Mpc$^{-1})$ and deceleration parameter $q_0 = 0.5$ throughout this paper.

First, previous measurements show that this system has a rest-frame Lyα absorption equivalent width of 0.65 Å, implying an H I column density $N(\mathrm{H\ I}) = 10^{15.3} - 10^{17.6}$ cm^{-2} for a reasonable range of Doppler parameter (Chen et al. 2000b). This suggests that the absorber is a partial Lyman limit system at $z \approx 0$, which may provide a benchmark for comparison against Lyman limit systems (LLS) at high redshift. Second, two galaxies have been identified at the absorber redshift (Spinrad et al. 1993; Chen et al. 2000b). A detailed study of this absorption system therefore serves to constrain the physical properties of the galaxy environment, which offers a unique opportunity to investigate whether QSO absorption line systems arise in extended halos of individual galaxies or in intragroup media of galaxy groups.

2. ANALYSIS

Spectroscopic observations of PKS 0405−1219 were accessed from the HST data archive. The QSO was observed with HST using STIS in echelle mode with a $0''.2 \times 0''.06$ slit and the E140M grating ($R = 45800$ or 6.7 km s^{-1}) for a total exposure time of 27,208 s. The observations were carried out in two visits of five exposures each. The individual echelle spectra were reduced, extracted, and calibrated using standard pipeline techniques, and were coadded to form an averaged spectrum and a 1 σ error array per visit using our own reduction program. To form a final spectrum for absorption line studies, we normalized each coadded spectrum with a best-fit, low-order polynomial continuum and calculated a weighted average of the normalized spectra with the weighting factor determined by the squares of the SNR. The final spectrum covers a spectral range that spans from ≈ 1140 Å to ≈ 1730 Å and has SNR of ≈ 7 per resolution element in most of the spectral region.

We identified absorption features produced by H^0, C^+, N^+, O^0, Si^+, Si^{++}, Si^{+3}, possibly Fe^+ and Fe^{++}; and most interestingly we identified the absorption doublets produced by N^{+4} and O^{+5} for the absorption system at $z = 0.167$. Figure 1 shows the velocity profiles of all transitions with $v = 0$ corresponding to redshift $z = 0.1671$.

We first determined the H I column density by fitting Voigt profiles to the saturated Lyα and Lyβ absorption lines using the VPFIT package provided by R. Carswell and J. Webb. But because of the degeneracy between N(H I) and b for saturated Voigt profiles, we found that while the profile fitting procedure yielded a best fit[‡] $N(\text{H I}) = 10^{15.8\pm0.2}$ cm^{-2} with $b = 35$ km s^{-1}, solutions with similar reduced χ^2 range from $\log N(\text{H I}) = 15.7$ to $\log N(\text{H I}) = 17.0$ for b from 36 km s^{-1} to 26 km s^{-1}. Additional spectroscopic observations of the QSO in the far UV wavelength range (e.g. with the Far Ultraviolet Spectroscopic Explorer) are required to precisely measure the H I column density using higher-order Lyman series absorption. Despite the large uncertainty in the H I column density, we confirmed that the absorber is a partial LLS with $N(\text{H I}) \approx 10^{16}$ cm^{-2}. Next, we measured the ionic column densities using the apparent optical depth method (Savage & Sembach 1991), which provides an accurate column density estimate for resolved, unsaturated absorption lines. The column density measurements are presented in Table 1, which lists the ions, the corresponding rest-frame absorption wavelength λ_0, and the estimated ionic column densities $\log N$ together with the associated errors in the first three columns. Lower limits indicate that the lines are saturated in the STIS spectrum.

The detections of N^{+4} and O^{+5} at the absorber redshift are very interesting, because these ions are often believed to form through collisional ionization in hot gas clouds. We show in Figure 1 that all the ions except N^{+4} and O^{+5} have consistent profile signatures that trace the partial LLS, while the N V and O VI doublets appear to be broad and have velocity centroids blue-shifted by ≈ 30 km s^{-1} from the other ions. The differences in kinematic signatures strongly indicate that the N V and O VI doublets and the partial LLS traced by the other ions do not arise in the same regions. For this reason, we studied the physical environment separately for the two gas regions.

We first determined the temperature of the partial LLS using the b parameters estimated from a Voigt profile analysis for the unsaturated lines produced by Si^{+} and N^{+}. The estimates of the b parameters are presented in the forth column of Table 1. We found that $b = 9.9 \pm 0.9$ km s^{-1} for

---

[‡]The solutions included additional components in the blue wing of the Lyα line which do not impact the N(H I) of the absorption system at $z = 0.167$.

Si^{+} and $b = 11.6 \pm 1.0$ km s^{-1} for N^{+}. Because both thermal motion and bulk motion contribute to the measured Doppler parameter and because Si^{+} and N^{+} share the same bulk motion, we solved for $b_{\rm bulk}$ and T. We found that $b_{\rm bulk} = 6.8 \pm 2.9$ km s^{-1} and $T \approx 7.4 \times 10^4$ K with a 1 σ lower limit being $T \approx 2.7 \times 10^4$ K and 1 σ upper limit being $T \approx 1.5 \times 10^5$ K.

According to Sutherland & Dopita (1993), collisional ionization models cannot produce the observed relative abundances for the Si ions at temperatures between $T \approx 2.7 \times 10^4$ K and $T \approx 1.5 \times 10^5$ K. It is therefore very unlikely that the partial LLS is collisionally ionized. We determined the ionization state of the partial LLS by comparing the column densities of H^0, Si^{+}, Si^{++}, and Si^{+3} with the predictions from a series of photoionization models calculated using the CLOUDY software package (Ferland 1995). Considering a plane-parallel geometry for gas of solar metallicity, we calculated the column density predictions for various ions. The predictions of relative ionic column densities are fairly insensitive to the adopted metallicity and H I column density (for optically thin gas) in the CLOUDY calculations, even though the absolute predictions may vary accordingly. Therefore, we were able to place reasonably tight constraints on the ionization parameter, which is the ratio of incident ionizing photons to the total hydrogen number density, $U \equiv \phi_{912}/\,c n_{\rm H}$, by comparing the relative abundances of the Si ions. We found $\log U = -2.64 \pm 0.07$[§] using the $Si^{+}/\,Si^{+3}$ ratio, which is in a good accordance with the limits derived from $Si^{++}/\,Si^{+}$ and $Si^{+}/\,Si^{++}$. Given the best estimated U, we determined the total hydrogen column density $N({\rm H})$, ionization fraction x, hydrogen number density $n_{\rm H}$, and the spatial extent for the partial LLS. The results are summarized in Table 2.

Finally, we estimated the elemental abundances of the partial LLS using the ionization fraction correction calculated from the CLOUDY model for an ionization parameter $\log U = -2.64$. The results are shown in the last column of Table 1 for an H I column density $\log N(\text{H I}) = 16.5$. Adopting the largest possible H I column density $N(\text{H I}) = 10^{17}$ cm^{-2}, we found that the partial LLS would have 1/10 solar abundance determined for carbon and silicon and 1/5 solar abundance

---

[§]The error in U is based solely on the error in $N(\text{SiII})/N(\text{SiIV})$ and does not account for the systematic errors associated with the simplified assumptions inherent to the CLOUDY calculations.

for nitrogen. Adopting the best fit N(H I) of $10^{15.7}\,\mathrm{cm}^{-2}$, we derived a super-solar metallicity for the system. In addition, we also estimated the chemical abundance using the O I absorption line. In regions where the resonant charge-exchange reaction between oxygen and hydrogen becomes dominant, the column density ratio [O I/ H I] provides a direct estimate of the elemental abundance of oxygen. Otherwise, the ratio [O I/ H I] provides a lower limit to the estimate of oxygen elemental abundance. We derived a metallicity of at least 1/2 solar for oxygen and contend that the absorbing gas has been heavily enriched in metals.

The results obtained from the CLOUDY analysis demonstrated that a single photoionization model cannot explain the observed column densities of the O^{+5} and N^{+4} ions. At the extreme upper limit $\log U = -2.2$, both O VI and N V are predicted to be at least 0.4 dex less abundant than Si IV. But our measurements indicate that O VI and N V are at least 0.4 dex more abundant than all the Si ions. In agreement with our assessment of the kinematic characteristics, the CLOUDY predictions further demonstrated that O^{+5} and N^{+4} do not arise in the partial LLS. Under the assumption of collisional ionization, the temperature of O^{+5} and N^{+4} may be derived by comparing their column density ratio with a series of collisional ionization models. According to Shapiro & Moore (1976), an optically thin gas of solar relative abundance at thermal equilibrium with $N(\mathrm{O\ VI})/\,N(\mathrm{N\ V}) = 6.9 \pm 1.5$ has a temperature of $T = (2.6 \pm 0.1) \times 10^5$ K[¶]. At this temperature, we calculated the total hydrogen column density using the ionization fraction correction calculated by Sutherland & Dopita (1993). We also estimated the bulk motion of these ions by fitting Voigt profiles to the O VI and N V absorption doublets. The results are summarized in Table 2.

3. DISCUSSION

Our analysis of the STIS echelle spectrum revealed unusual properties of the Lyα absorption system at $z = 0.167$. We found a chemically enriched, warm gas region giving rise to the partial

[¶]The estimated temperature may differ by only $\approx 5\%$ if the relative abundance of oxygen to nitrogen is twice the solar.

LLS and a hot gas region giving rise to O^{+5} and N^{+4} along the QSO line of sight. Two galaxies have been identified in the field of PKS0405−1219 at the absorber redshift (Spinrad et al. 1993; Chen et al. 2000b): (1) an elliptical galaxy at $z = 0.1667$ with an angular distance $\theta = 40.4''$ to the QSO (corresponding to an impact parameter $\rho = 74.9\ h^{-1}$ kpc) and a rest-frame K-band luminosity $L_K = 1.20\ L_{K_*}$ and (2) a spiral galaxy at $z = 0.1670$ with $\theta = 33.9''$ (corresponding to $\rho = 62.8\ h^{-1}$ kpc) and $L_K = 0.02\ L_{K_*}$. While it is not uncommon to find tenuous gas at large galactic distance ($\rho \sim 100\ h^{-1}$ kpc) around nearby elliptical galaxies (e.g. Fabbiano, Kim, & Trinchieri 1992) or groups of galaxies (e.g. Mulchaey et al. 1996), it is very surprising to find metal-enriched, high-column density gas at this large distance. Furthermore, our column density estimates for O^{+5} and N^{+4} are comparable to the measurements obtained for highly ionized gas in the Galactic halo, most of which is believed to arise near the galactic plane (Savage, Sembach, & Lu 1997; Savage et al. 2000). The spectral characteristics of the elliptical galaxy exhibit signs of recent star formation (Spinrad et al. 1993), therefore the physical process that initiated the recent star formation might be responsible for transporting metals to large galactic distance.

In light of the different kinematic characteristics between the partial LLS and the O VI absorbing cloud, it seems likely that the partial LLS is embedded within a larger volume of hot O VI gas that is spread out in a galactic halo or an intragroup medium. But it is very rare to detect hot gas at a temperature $T \approx 2 \times 10^5$ K, where the cooling function is the most effective (see e.g. Spitzer 1978). In order for the the hot gas to remain at this temperature, we derive rough estimates of the underlying mass and gas number density assuming a simple isothermal halo. Specifically, a more massive system would have a higher virial temperature and consequently raise the gas temperature through gravitational interaction. A higher gas density would increase the cooling rate and consequently lower the gas temperature through collisional cooling processes. We estimate the mass of the galaxy or galaxy group that supports the extended hot gas by requiring a virial temperature $T \approx 2.5 \times 10^5$ K and find that a total mass of $\approx 1.5 \times 10^{12} M_\odot$ for a half-mass radius $r_h \approx 0.35$ Mpc. We estimate the number density by requiring a cooling time longer than the dynamical time, $t_{\rm dyn} \approx \pi R/\sqrt{2}\sigma$, and find that the number density of the absorbing gas should be $\lesssim 3 \times 10^{-5}$ cm^{-3} for a velocity dispersion $\sigma \approx 60$ km s^{-1} at $R \approx 100$ kpc (implying $t_{\rm dyn} \approx 3.5$ Gyr).

Although two galaxies have been identified at the absorber redshift, it is very difficult to determine whether the absorbing gas originates in extended halos of individual galaxies or in an intragroup medium of an underlying galaxy group without a more complete spectroscopic survey of galaxies in this field. We can however derive constraints on the properties of the galaxies either individually or collectively for both scenarios based on all the available measurements.

Comparison of galaxies and Lyα absorption systems along common lines of sight has shown that the gaseous extent r of galaxies of all morphological types scales with galaxy K-band luminosity L_K according to $r \propto L_K^{0.28\pm0.08}$ (Chen et al. 2000b). According to these authors, we expect that the extended gas of the spiral galaxy would contribute an H I column density of no more than 3.2×10^{14} cm^{-2} at $\rho = 62.8\ h^{-1}$ kpc, but that the extended gas of the elliptical galaxy would easily contribute an H I column density of 10^{17} cm^{-2} at $\rho = 74.9\ h^{-1}$ kpc. By carefully examining deep images obtained both with HST using the Wide Field and Planetary Camera 2 with the F702W filter and with the IRTF 3 m telescope using the K' filter, we find that if there are unidentified dwarf galaxies at the absorber redshift and closer to the QSO line of sight, then they cannot be brighter than 0.02 L_{K_*}. It is therefore more likely that the absorbing clouds should follow the halo motion of the bright elliptical galaxy if the absorption system arises in individual galactic halos. Assuming that the absorption system is produced in the gaseous halo of the elliptical galaxy and adopting a King profile for the gas distribution around the elliptical galaxy, $n(r) \propto 1/[1 + (r/r_c)^2]$, we derive a total gas mass of $M_{\rm gas} \lesssim\ 10^{10} M_\odot$ within a radius $\rho < 100\ h^{-1}$ kpc for a core radius between $r_c = 10$ and 50 kpc and for a unit filling factor. The estimated gas mass within 100 h^{-1} kpc is significantly lower than the dynamical mass $3.6 \times 10^{11} M_\odot$ estimated for $M/L_K \approx 6.6$, implying a small gas fraction in the inner part of the elliptical galaxy.

Mulchaey et al. (1996) suggested that an intragroup medium of temperature just below the detection threshold of existing X-ray observations may reveal itself through the imprint of high-ionization absorption lines, such as O VI and Ne VIII, in the spectra of background QSOs. Recent observations also indicated that some O VI absorption lines originate in an environment of excess galaxy counts (Tripp, Savage, & Jenkins 2000). Adopting the $\sigma - T$ correlation obtained for groups of galaxies in X-ray (Mulchaey & Zabludoff 1998) and extrapolating to lower temperature, we find a corresponding velocity dispersion of $\sigma \approx 60$ km s^{-1} for $T \approx 2.5 \times 10^5$ K, which is very close to the estimated bulk motion for the O VI absorbing gas. Based on the estimated velocity dispersion, we derive a total mass of $M \approx 1.5 \times 10^{12} M_\odot$ for the galaxy group assuming a virialized isothermal halo and a half-mass radius $r_h \approx 0.35$ Mpc. Therefore, we find that if the absorption system is produced in the intragroup medium, then the total mass of the underlying galaxy group is comparable to the Local Group (Courteau & van den Bergh 1999).

The absorber at $z = 0.167$ exhibits striking resemblance to the LLS at $z = 0.79$ presented by Bergeron et al. (1994) both in physical properties of the absorbing gas and in the surrounding galaxy environment. The absorber at $z = 0.79$ was found to have a metallicity of a half solar and likely be embedded in a hot O VI gas of $T \approx 2 \times 10^5$ K. A group of galaxies have been identified at the absorber redshift, the closest of which is at 110 h^{-1} kpc to the QSO line of sight. If the two systems are representative of low-redshift LLSs, then the relationship between LLSs and surrounding galaxies may provide important clues regarding the chemical enrichment history and dynamics of gas in intragroup media. On the other hand, various models have been proposed to explain extended H I gas at large galactic distance, including satellite accretion (Wang 1993), tidal debris (Morris & van den Bergh 1994), and two-phase galactic halos (Mo & Miralda-Escudé 1996). Of these models, accretion from a star-forming satellite galaxy is the most likely to explain the observed high-metallicity gas at large distance to regular-looking galaxies at $z = 0.167$.

Finally, comparison of the absorber at $z = 0.167$ and known high-redshift LLSs (Köhler et al. 1999; Lopez et al. 1999; Prochaska 1999; Prochaska & Burles 1999; Rauch et al. 1999) shows that all but one (Rauch et al.) of these Lyman limit absorbers have similar estimates of the ionization parameter U. If the majority of LLSs continue to exhibit $\log U \approx -2.5$ at all epochs, then it clearly calls for the question whether these systems share similar physical properties such as gas temperature.

It is a pleasure to thank Jacqueline Bergeron, Alan Dressler, Ken Lanzetta, Pat McCarthy, John Mulchaey, Michael Rauch, Ben Weiner, and Ray Weymann for helpful discussions. We acknowledge the STIS GTO team for obtaining the QSO spectra (program identification number 7576). JXP acknowleges support from a Carnegie postdoctoral fellowship and would like to thank ESO for their hospitality.

REFERENCES

Bergeron, J. & Boissé, P. 1991, A&A, 243, 344

Bergeron, J., Petitjean, P. et al. 1994, ApJ, 436, 33

Chen, H.-W., Lanzetta, K. M., Webb, J. K., & Barcons, X. 1998, ApJ, 498, 77

———. 2000a, ApJ submitted

———. 2000b, in preparation

Courteau, S. & van den Bergh, S. 1999, AJ, 118, 337

Fabbiano, G., Kim, D.-W., & Trinchieri, G. 1992, ApJS, 80, 531

Ferland, G. J. 1995, HAZY, a Brief Introduction to Cloudy (Univ. Kentucky Phys. Astron. Dept. Internal Rep.)

Haehnelt, M. G., Steinmetz, M., & Rauch, M. 1998, ApJ, 495, 647

Haardt, F. & Madau, P. 1996, ApJ, 461, 20

Köhler, S., Reimers, D., Tytler, D. et al. 1999, A&A, 342, 395

Lanzetta, K. M., Bowen, D. V., Tytler, D., & Webb, J. K. 1995, ApJ, 442, 538

Lopez, S., Reimers, D., Rauch, M., & Sargent, W. L. W. 1999, ApJ, 513, 598

Mo, H. J. & Miralda-Escudé, J. 1996, ApJ, 469, 589

Morris, S. L. & van den Bergh, S. 1994, ApJ, 427, 696

Mulchaey, J. S., Davis, D. S., Mushotzky, R. F., & Burstein, D. 1996, ApJ, 456, L5

Mulchaey, J. S. & Zabludoff, A. I. 1998, ApJ, 496, 73

Pettini, M., Smith, L. J., King, D. L., & Hunstead, R. W. 1997, ApJ, 486, 665

Prochaska, J. X. & Wolfe, A. M. 1997, ApJ, 487, 73

———. 1998, ApJ, 507, 113

———. 1999, ApJS, 121, 369

———. 2000, ApJ, 533, L5

Prochaska, J. X. 1999, ApJ, 511, 71

Prochaska, J. X. & Burles, S. M. 1999, AJ, 117, 1957

Rauch, M., Haehnelt, M. G., & Steinmetz, M. 1997, ApJ, 481, 601

Rauch, M., Sargent, W. L. W., & Barlow, T. A. 1999, ApJ, 515, 500

Savage, B. D., Sembach, K. R., & Lu, L. 1997, AJ, 113, 2158

Savage, B. D., Sembach, K, R., Jenkins, E. B. et al. 2000, ApJL, in press

Shapiro, P. R. & Moore, R. T. 1976, ApJ, 207, 460

Shull, J. M, Roberts, D., Giroux, M. L., Penton, S. V., & Fardal, M. A. 1999, AJ, 118, 1450

Spinrad, H., Filippenko, A. V., Yee, H. K. et al. 1993, AJ, 106, 1

Spitzer, L. 1978, in Physical Processes in the Interstellar Medium

Sutherland, R. S. & Dopita, M. A. 1993, ApJS, 88, 253

Wang, B. 1993, ApJ, 415, 174

This manuscript was prepared with the AAS LaTeX macros v4.0.

Fig. 1.— Velocity profiles of absorption lines identified for the absorption system at $z = 0.167$ in the STIS spectrum with $v = 0$ corresponding to redshift $z = 0.1671$. The identification of each transition is indicated in the lower right corner of each panel. The upper and bottom dashed lines indicate the continuum and zero levels, respectively. The dash-dotted lines indicate the velocity centroids. Contaminating features from other sources that are excluded in our analysis are indicated by dotted curves.

Table 1. Estimates of Column Densities, Doppler Parameters, and Abundances

Species	λ_0	log N (cm^{-2})	b (km s^{-1})	[X/H][a]
H I . . .	1025.72	> 15.7	34.7 ± 2.5	...
	1215.67	> 15.7	...	...
C II . .	1036.79	> 14.10	...	...
	1334.53	14.27 ± 0.09	...	-0.33
N II . .	1083.99	> 14.25	11.6 ± 1.0	0.27
N V . .	1238.82	13.84 ± 0.07	50.2 ± 7.0	...
	1242.80	13.91 ± 0.06	...	...
O I . . .	1302.17	13.68 ± 0.14	...	0.25
O VI .	1031.93	14.67 ± 0.16	72.6 ± 4.9	...
	1037.62	14.76 ± 0.07	...	...
Si II . .	1190.42	13.22 ± 0.07	9.9 ± 0.9	...
	1193.29	13.29 ± 0.05	...	...
	1260.42	> 13.16	...	...
	1304.37	13.40 ± 0.12	...	-0.37
Si III .	1206.50	> 13.33	...	> -0.76
Si IV .	1393.76	13.18 ± 0.05	...	...
	1402.77	13.49 ± 0.07	...	-0.45

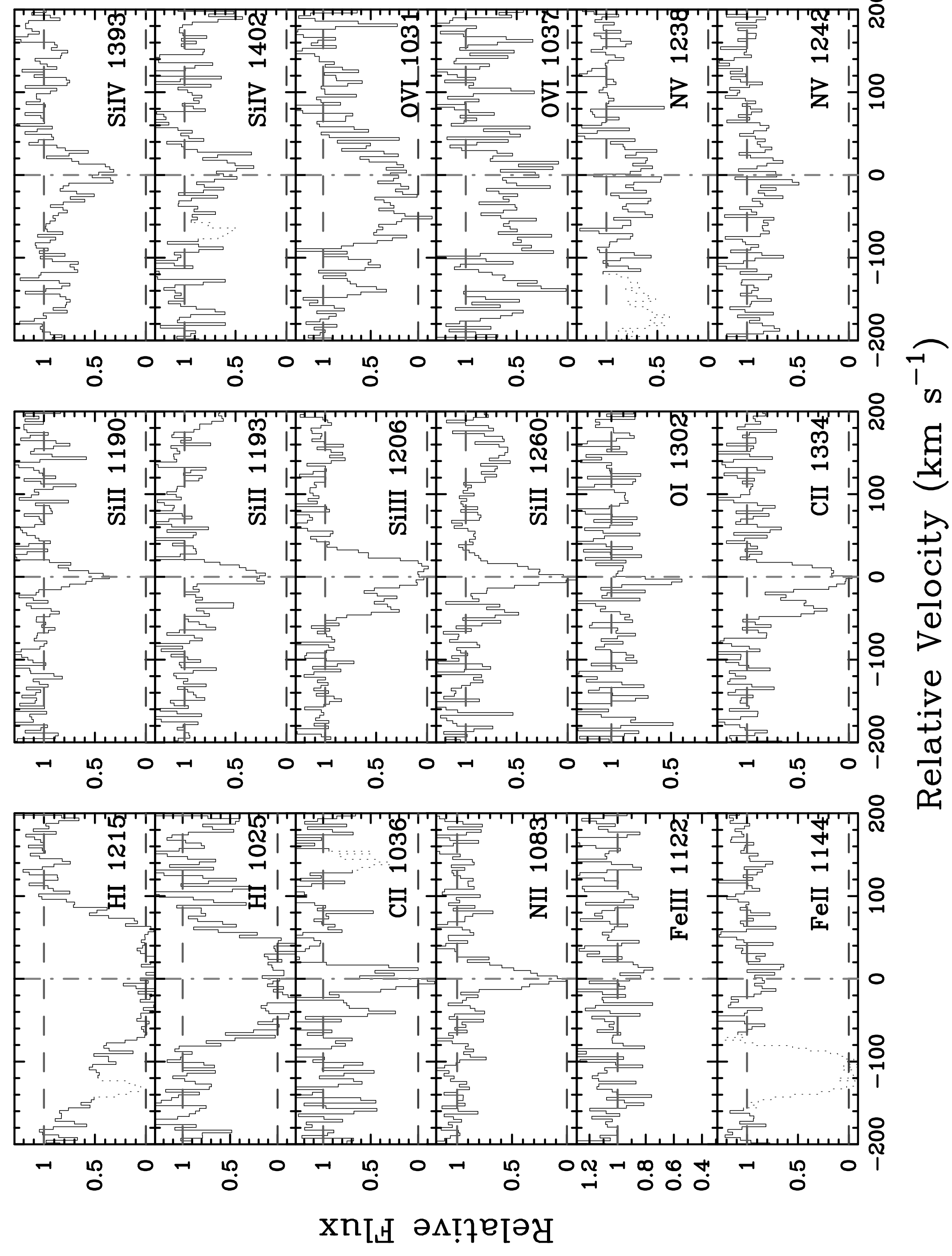
[a][X/H] is defined as $\log\,[N(\mathrm{X})/\,N(\mathrm{H})] - \log\,[\mathrm{X}/\,\mathrm{H}]_\odot$. We assumed log N(H I) = 16.5 for the abundance estimaates. Increasing (decreasing) N(H I) by 0.5 dex decreases (increases) the abundance measurements by 0.5 dex.

Table 2. Physical Parameters of the Absorption System at $z = 0.167$

Physical Parameter	Partial LLS[a]	N V, O VI[b]
Ionization parameter log U	-2.64 ± 0.07	...
Ionization fraction x	0.996	...
Hydrogen column density log N(H) .	18.86 ± 0.07	≈ 18.6
Hydrogen number density $n_{\rm H}$ (cm^{-3})	6×10^{-4}	$< 3 \times 10^{-5}$
Cloud size l (kpc)	≈ 4	...
Bulk motion $b_{\rm bulk}$ (km s^{-1})	≈ 7	≈ 70
Temperature T (K)	7.4×10^4	2.5×10^5
Chemical abundance [Z/H]	> -0.1	...

[a] N(H),$n_{\rm H}$, and l were estimated by adopting an ionizing radiation intensity $J_{912} \approx 2 \times 10^{-23}$ ergs s^{-1} cm^{-2} Hz^{-1} sr^{-1} at $z = 0$ estimated by Shull et al. (1999).

[b] N(H) was estimated based on the measured O VI column density, corrected for the ionization fraction of oxygen at $T \sim 5.4 \times 10^5$ K assuming a solar abundance. $n_{\rm H}$ was estimated by requiring a cooling time comparable to or greater than the dynamical time.



HI 1215
HI 1025
CII 1036
NII 1083
FeIII 1122
FeII 1144
SiII 1190
SiII 1193
SiIII 1206
SiII 1260
OI 1302
CII 1334
SiIV 1393
SiIV 1402
OVI 1031
OVI 1037
NV 1238
NV 1242
Relative Flux
Relative Velocity (km s−1)